

## Transportation Mission Based Optimization of Heavy Vehicle Fleets including Propulsion Tailoring

TOHEED GHANDRIZ

Department of Mechanics and Maritime Sciences  
CHALMERS UNIVERSITY OF TECHNOLOGY  
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THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING  
IN  
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TRANSPORTATION MISSION BASED  
OPTIMIZATION OF HEAVY VEHICLE  
FLEETS INCLUDING PROPULSION  
TAILORING

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Department of Mechanics and Maritime Sciences  
Chalmers University of Technology  
SE-412 96 Göteborg  
Sweden  
Telephone: +46 (0)31-772 1000

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Toheed Ghandriz

Department of Mechanics and Maritime Sciences

Chalmers University of Technology

## Abstract

Over decades freight vehicles were produced for a wide range of operational domains so that vehicle-manufacturers were not concerned much about the actual use-cases of the vehicles. Environmental issues, costumer expectations along with growing demand on freight transport created a competitive environment in providing better transportation solutions. In this thesis, it was proposed that freight vehicles can be designed more cost- and energy-efficiently targeting rather narrow ranges of operational domains and transportation use-cases. For this purpose, optimization-based methods were applied to deliver customized vehicles with tailored propulsion components that fit best given transportation missions and operational environment. Optimization-based design of vehicle components showed to be more effective considering optimization of transportation mission infrastructure simultaneously, including charging stations, routing and fleet composition and size, especially in case of electrified propulsion. It was observed that by implementing integrated vehicle hardware-transportation optimization, total cost of ownership can be reduced up to 35%, in case of battery electric heavy vehicles.

Furthermore, throughout thesis, the effect of propulsion system components size on optimal energy management strategy in hybrid heavy vehicles was studied; a methodology for solving fleet-size and mix-vehicle routing problem including enormous number of vehicle types were introduced; and the impact of Automated Driving Systems on electrified propulsion was presented.

**Keywords:** transportation mission, propulsion system tailoring, optimization, heterogeneous heavy vehicle fleet, electrified propulsion, electromobility, Automated Driving Systems, optimal energy management, total cost of ownership, fleet sizing



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# Thesis

This thesis comprises a short summary and the following appended papers.

- I. Ghandriz, T., Hellgren, J., Islam, M., Laine, L., and Jacobson, B., *Optimization Based Design of Heterogeneous Truck Fleet and Electric Propulsion*. In: Proceedings of the 19th IEEE International Conference on Intelligent Transportation Systems, Rio de Janeiro, Brazil, pp. 328-335, 2016.
- II. Ghandriz, T., Laine, L., Hellgren, J., and Jacobson, B., *Sensitivity Analysis of Optimal Energy Management in Plug-in Hybrid Heavy Vehicles*. In: Proceedings of the 2nd IEEE International Conference on Intelligent Transportation Engineering, Singapore, pp. 320-327, 2017.
- III. Ghandriz, T., Islam, M., Hellgren, J., Jacobson, B., and Laine, L., *Transportation-mission-based Optimization of Heterogeneous Heavy-vehicle Fleet Including Electrified Propulsion, Powertrain Tailoring, and Fleet Sizing*. Submitted to European Journal of Operational Research, 2018.
- IV. Ghandriz, T., Jacobson, B., M., Laine, L., and Hellgren, J. *The Impact of Automated Driving Systems on Road Freight Transport and Electrified Propulsion of Heavy-vehicles*. Submitted to Journal of Transportation Research Part C: Emerging Technologies, 2018.

In paper (I), the text was mainly written by Ghandriz, with valuable input from all authors. The simulation model was initially built by Ghandriz with the help of Dr. Hellgren in providing input data and electric motors energy loss model, and Professor Jacobson and Dr. Islam in model validation. The idea behind the paper belongs to Professor Laine and Dr. Hellgren.

In paper (II), the text was mainly written by Ghandriz, with valuable input from Professor Jacobson. The simulation model was built by Ghandriz

with the input data from Dr. Hellgren. The idea behind the paper belongs to Professor Laine and Dr. Hellgren.

In paper (III), the text was written and the solution methodology was mainly proposed by Ghandriz, with valuable input from all authors. The simulation model was built by Ghandriz with the input data from Dr. Hellgren and Professor Laine. The idea behind the defined problem belongs to Professor Laine and Dr. Hellgren.

In paper (IV), the text was mainly written by Ghandriz, with valuable input from all authors. The simulation model was built by Ghandriz with the help of Professor Jacobson in improving and analyzing the results. The idea behind the paper belongs to Ghandriz.

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## INCLUDED PAPERS



# Chapter 1

## Introduction

### 1.1 Motivation

Predictions reveal an annual volume growth in freight transport by 8% in last mile deliveries to end costumers and by 4% in heavy-vehicles trucking until 2025 [25]. The growth in volume requires more capacity of freight transport and consequently an increase in emissions and environmental damage is expected. According to European Commission [14], contribution of heavy-vehicles in producing CO<sub>2</sub> emissions rises to 25% of road transport in Europe, emphasizing the necessity of employing new effective solutions to meet sustainability requirements. Furthermore, growing demand on freight transport, pressure from regulators to comply with environmental standards, increasing costumers expectations along with technological advancements create a competing environment for industrial players, original equipment manufacturer (OEMs) and logistic planners. As [25] reports, transport volume growth is expected to add only 40% to revenue increase of truck industry while the additional 60% is due to implementation of new technologies. Therefore, future success of OEMs depends on their agility and quick adaptation, development and implementation of new technologies.

Two important compounds leading to agility of developing and implementing new technologies are mathematical modeling and optimization. Optimization based design of vehicle systems using mathematical models with an acceptable level of fidelity promotes solutions that in many cases are only possible to obtain after long discussions and efforts while having a good engineering knowledge of the system. In some cases, performing excursively

trial and error runs relying on engineering judgments is not sufficient to see interconnection between all contributing factors, thereby leading to infeasible or poor solutions. On the other hand, if there is a deficient understanding about the layout, deciding factors, and constraints of the problem, then the result of optimization cannot be trusted. As regards freight transportation with many contributing factors, an accurate description must be obtained via clear communications between transportation companies, logistic industries and vehicle-manufacturers. Thus, a close cooperation between these stakeholders should be taken seriously during strategic levels of decision making.

In freight transport, there are numerous contributing factors. Recognizing and understanding them all to put in a mathematical model and optimization process to come up with the best solutions might not seem to be realistic. However, developing such optimization models is possible for closed-boundary systems and specific use-cases. Furthermore, if the optimization is repeated for many use-cases, some similar trends can be seen between solutions and some generalized conclusions can be drawn. Moreover, considering closed-boundary use-cases opens up possibilities to find more cost- and energy-efficient customized vehicle-transport solutions.

Through implementation of optimization processes, this thesis addresses the following main problems.

- How to enhance road freight transportation efficiency and profitability including tailoring the propulsion system of freight vehicles, when electrically-propelled axles are allowed on any unit?
- How is the vehicle propulsion optimization coupled with vehicle operational domain and how these two affect each other?

## 1.2 Envisioned solution

Profitability is a key factor for transportation companies to move towards new solutions; therefore, total cost of fleet ownership (TCO) is considered as an optimization objective in most of the cases in this thesis. Optimization design variables vary between problems studied. They relate to transportation mission as well as vehicle hardware, in particular propulsion system. Within the propulsion system, the thesis especially considers adding electric propulsion on some units in long combination vehicles. Transportation mission related design variables include route, fleet composition, fleet size, number of trips, speed, and infrastructure such as loading/unloading scheme

and charging station (for electric vehicles) at each node of the transportation network. Correspondingly, vehicle-pertaining design variables include vehicle size, type of propulsion system i.e. a choice between combustion-powered, battery electric and hybrid powertrain, internal combustion engine (ICE) size, type of electric motors, number of powered axles, recharging power, and size and type of the batteries.

Electrified propulsion proved to be one of the main solutions of providing a green transportation. As literature and real-world experience of transportation companies suggest, the profitability of battery electric vehicles can be improved by customizing the vehicle hardware. Indeed, this thesis shows interconnection between different cost indicators and considering all in an integrated optimization process makes a fleet of battery electric heavy vehicles competitive to their conventional counterparts in a wide range of transportation missions.

Integrated design of a fleet comprising electric and combustion-powered vehicles result in up to 50% reduction in TCO. It has been observed that TCO might increase up to 35% if integrated vehicle hardware-infrastructure simultaneous optimization is not considered in case of battery electric heavy vehicles; for example, if a vehicle designed to operate in a traveling range (before reaching next charging station) of 80 km is used, instead, in missions with a traveling range of 10 km. Furthermore, the highest potential revenue offered by new technologies in near future comes from deploying Automated Driving Systems–Dedicated Vehicles. It was also shown that these kind of heavy vehicles might get a huge benefit by simultaneous optimization of vehicle hardware-infrastructure.





# Chapter 2

## Method

In this thesis, mathematical models included descriptions of transportation task, operational environment and vehicle model. Transportation was described by a distribution network of nodes with pick-up and delivery demands along with routes between them. The input data about transportation task and operational environment should be static and deterministic; meaning that they do not evolve with time and there is no level of uncertainty [31]. Static and deterministic data were needed owing to the fact that optimizations of vehicle hardware-transportation must be done during the strategic level of decision making. Real time tactical and operational actions could not be included as design variables since the optimized vehicle hardware setup cannot be changed while driving on-road. However, a representative data might be used which represent the most likely situations [23], [30]; or the extreme cases where the vehicle is expected to operate. An exception was the chance of oversizing ICE and batteries in hybrid vehicles which was discussed in paper II.

Operational environment was described by road length and topography with a prescribed reference speed and no traffic disturbances. Such a description is similar to that of Global Truck Application [13], Global Transport Application (GTA) [29] or numerical description of road transport missions reported in [28], with a difference that it is incorporated with the data of specific transportation network use-cases.

Vehicle model described propulsion system and dynamic longitudinal motion on-road, including ICE, electric motors (EMs) and battery models. Battery models included a description of battery degradation. No gear-shift and road grip limit was considered. Vehicle model was used to test vehicle per-

formance and for estimation of energy consumption.

Varying the design variables, simulation of these models was repeated numerously within the optimization process until a solution was obtained. In addition, depending on the problem in hand, for example, in case of fleet vehicle-infrastructure optimization and fleet sizing, similar optimization processes needed to be solved for many different scenarios. Thus, simulation time needed to be as short as possible. Requirement on short simulation time leads to implementation of simple mathematical models. The required level of fidelity and complexity should be determined as trade-offs between simulation time and reliability of simulation results. The reliability of simulation results can be examined against real-world tests or by sensitivity analysis and comparing them to the results obtained by a model with a higher fidelity. Moreover, the mathematical model should be sensitive enough to included optimization design variables. A comparison of a combustion-powered heavy vehicle (CPHV) including the ICE model used in this thesis with that of the high fidelity longitudinal model GSP [5] yielded only  $\pm 3\%$  error in diesel fuel consumption, on a operation mainly on highway, 160 km and 80 ton gross mass.

Furthermore, an optimization problem might yield unrealistic results without considering proper constraints. Constraints were imposed by transportation mission, operational environment, vehicle model and expected vehicle performance. Constraints related to vehicle performance are referred as “performance based standards”, [12], [32], [33] and [19], guarantee proper functionality of the vehicles along with on-road safety. Such constraints corresponding to vehicle longitudinal performance have been considered in most of the optimization problems defined in this thesis. A complete and compact set of constraints related to vehicle model and performance can be found in paper (IV) concerning combustion-powered and battery electric vehicles.

To examine the competitiveness of suggested solutions, total cost of ownership (TCO) has been used as an objective function through-out papers in this thesis. In some cases, the annual TCO per unit freight transported has been considered for fully loaded vehicles to make the comparisons independent of capacity utilization. It has been tried to include most of the important cost components into the cost structure both in terms of vehicle and transportation task. Depending on the problem, cost structure comprised driver wage, diesel fuel, electrical energy, maintenance, tax, insurance, battery degradation and replacements, loading–unloading costs, recharging-station installation, transport mission management related to Automated Driving Systems,

and depreciation of vehicle components such as chassis, driver cabin, electric motors, batteries, ICE and sensors and computers needed for object and event detection and response in case of Automated Driving Systems.

Design variables have been also selected such to reflect important aspects of vehicle-transportation design. Design variables belong to sets with discrete ranges. It has been shown in papers of this thesis that there exist interconnection between design variables and they all together influence TCO. The interconnection of design variables is more significant in case of electromobility and electric vehicles. According to [40, 9, 15, 41, 24, 7, 26, 27, 38, 39], payload, weight and volume of goods, purchase cost, operating range, utilization level, charging infrastructure, battery life, average speed, available routes, energy consumption, and logistics all contribute to electric heavy vehicles competitiveness. Indeed, in this thesis, it was shown that all these factors are interconnected and treating them simultaneously in a vehicle-transport optimization leads to better performance and profitability in wider range of missions.

The complexity of problem grows exponentially considering heterogeneous fleet optimization along with its composition and sizing. Many fleet vehicles hardware were optimized not being sure which one should be included in the fleet. The number of vehicle types reached billions which made the traditional approaches of solving vehicle routing problem (VRP) inapplicable. Various vehicle hardware resulted in a very large set of vehicle types which was not treated in literature. Moreover, adding several layers of complexity (i.e. charging station location, charging power and loading-unloading scheme) made the optimization problem extremely large. Reviews on different methods and similar works in VRP with a few vehicle types that are different in size and powertrain can be found in [10, 3, 18, 20, 16, 21, 11, 36, 9, 17, 37, 15, 22, 2, 21, 6, 4]. In this thesis, it was proposed that a close-to-optimum solution could be found by implementing a three-stage descend heuristics. See paper (III).



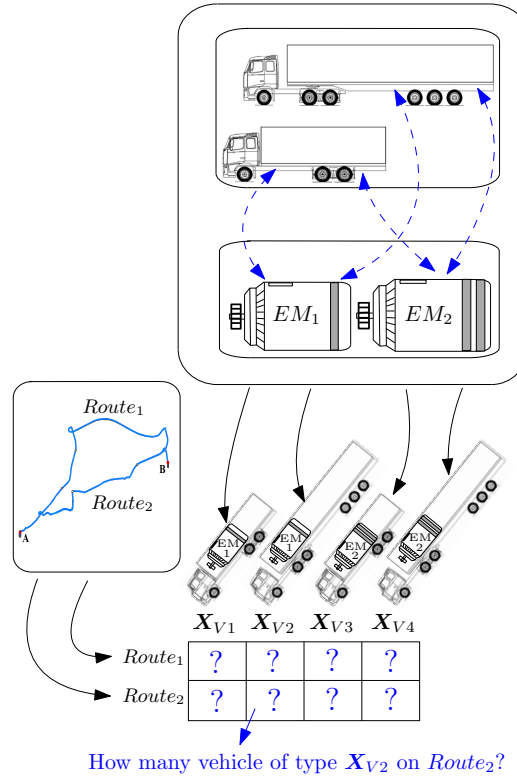
# Chapter 3

## Summary

### 3.1 Appended papers

The topic common in all papers is suggestion of cost- and energy-efficient vehicle-infrastructure solutions in road freight transportation.

**Paper (I)** defines the vehicle-infrastructure problem referred as heterogeneous vehicle routing problem (VRP) of a mixed fleet of vehicles with previously unknown propulsion system (HVRPMF-PUP). The problem was defined to answer the following question. How many vehicles of type  $X_{Vi}$  should be employed on route  $j$ , for  $i = 1, \dots, n_v$  and  $j = 1, \dots, n_r$ , to minimize total fleet ownership cost, where  $n_v$  and  $n_r$  denote total number of vehicle types and available routes? A simple example, including only two vehicle-pertaining design parameters (i.e. vehicle size and type of electric motors) and two routes, has been shown in Fig. 3.1. The case-study problem solved in paper (I) included only electrified propulsion and three routes. Vehicle-pertaining design parameters comprised vehicle size, type and number of electric motors, type and number of battery packs. Transportation task-related design parameters included selection of route and recharging power at each node (a selection between fast and slow charging). Design parameters have been selected from a discrete set and the reference speed was set according to the road limit speed. Simplicity of transportation task comprising only two nodes gave possibility of solving the problem by enumeration that is simulating all possible cases and picking up the best one. Thus it was possible to avoid complicated optimization procedures. The solution of the case study problem in paper (I) was not a heterogeneous fleet but a



**Figure 3.1:** A simple example of HVRPMF-PUP problem. (Reproduced from paper (I)).

single vehicle (i.e. a battery electric rigid truck) operating on a single route. The most important outcomes of the paper were according to followings.

- A cost-efficient vehicle is not necessarily an energy-efficient one.
- Long combination vehicles are not cost-efficient in missions with relatively short driving time. In such a mission the cost of hardware and driver are deciding factors.
- Performance based standards (PBS) acting as constraints reduce the size of the problem significantly by disqualifying many vehicles.
- If strong performance based characteristics are required the routing problem can be separated from powertrain design for certain transportation tasks. The problem is coupled otherwise.
- Considering route specific PBS results in designing cheaper vehicles.

In paper (I), the study was limited to battery electric vehicles, owing to user request. The general purpose of the thesis was to offer best vehicle-transport solutions. Therefore, propulsion systems such as combustion-powered and hybrid needed to be included. In case of hybrid propulsion, energy management strategy (EMS) in operational decision making level of vehicle actions plays an important role for energy-cost evaluation along with selection of propulsion components. EMS refers to a strategy of splitting the total requested power between ICE and electric motors. A poor EMS could result in oversizing batteries and ICE. Thus, selection of propulsion components, in general, is coupled with EMS. However, considering this coupling in vehicle-infrastructure optimization process in conceptual design stages causes a time resource problem, since simulation time of a sophisticated optimal EMS for the entire trip could take long. In order to investigate the possibility of implementing simpler EMS approaches than optimal EMS during vehicle-infrastructure optimization process, a sensitivity analysis was conducted to find out the effect of different propulsion system components on the value gained by different energy management strategies in **paper (II)**. Here, the “value” reflects the reduction in operational costs (or objective cost) such as cost of fuel, electric energy, battery wear, and also the cost of changing the ICE state from off to on, while obtained by a simpler approach. A simpler approach here refers to a rule-based (i.e. none-model based) or instantaneous EMS (IEMS) where the upcoming horizon is not considered. Dynamic programming has been used as a solution method for optimal EMS. The value gain of optimal EMS were calculated against variations in vehicle total mass, ICE size, battery size, electric motors maximum power, smoothness of traffic and inclusion/not inclusion of battery degradation in the cost function. The most important findings of paper (II) were as follows.

- Traffic flow has a large influence on EMS.
- Optimal EMS value gained is less than 4% of the objective cost in smooth traffic, while in a traffic with a relatively high variation of speed, it can reach up to 12%.
- Including battery degradation in cost function decreases battery wear of small batteries, while the total operational cost remains unchanged.
- Optimal EMS is not very much sensitive to vehicle total mass variations.
- Optimal EMS is more effective for a certain range of battery sizes.

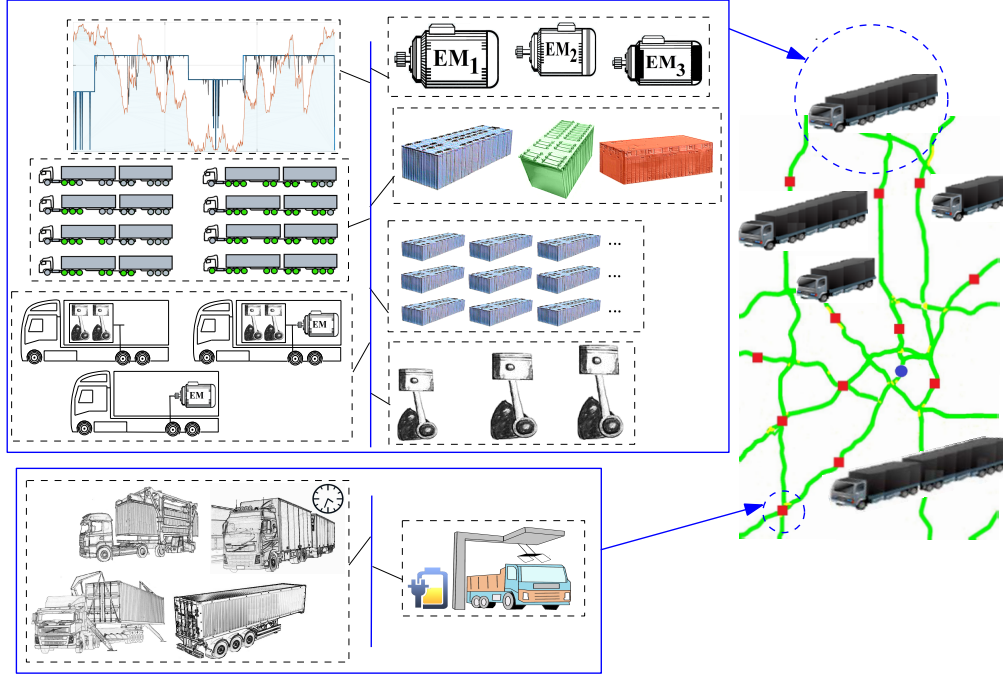
- Optimal EMS value gained is higher for larger ICEs, specially in non-smooth traffic.
- With only 4% difference in operational cost in smooth traffic , IEMS yields good enough results for concept evaluations.

Following paper (I) and (II), in **paper (III)**, the vehicle-transportation optimization problem was extended to include more regarding vehicle design and transport missions. Vehicle design parameters included vehicle-loading capacity, selection of propulsion system between combustion-powered, electrically powered, and hybrid vehicles, ICE size, type of electric motors, number of propelled axles, recharging power, and type and size of battery packs. Transportation design parameters, on the other hand, included routes, fleet size and composition, recharging-station locations, loading/unloading schemes, and number of trips. Owing to interconnection between operational environment and vehicle component design in terms of driving range, routing, location of charging stations, and factors affecting vehicle utilization level such as loading/unloading schemes, it was proposed to design vehicle-transportation in an integrated manner. An schematic of the problems is provided in Fig. 3.2. The problem considered could be classified as an extended version of fleet-size and mix-vehicle routing problem (FSMVRP) with many vehicle types, wherein both vehicle and transportation designs are simultaneously optimized. The number of vehicle types could reach billions, where, along with several layers of complexity other than routing, such as charging power and loading/unloading at each node, could result in enormously large number of design variables in the form presented in paper (I) (i.e. number of each vehicle type on each route), refer Fig. 3.1.

FSMVRP with enormous number of vehicle types has not been treated in literature. The following proposed postulates could help reducing the size of the problem.

- It is possible to obtain a reduced set of feasible and potentially “good” routes or missions, using a representative set of vehicle types.
- It seldom occurs that for a fixed loading capacity, several vehicles with different propulsion components setup are found optimum to perform similar tasks. Thus, for a given mission, vehicle size, and number of vehicles of the same type, there exists only one optimum vehicle type and mission infrastructure that yield lowest unit transportation cost.





**Figure 3.2:** *A schematic of design parameters of fleet vehicle–infrastructure optimization.*

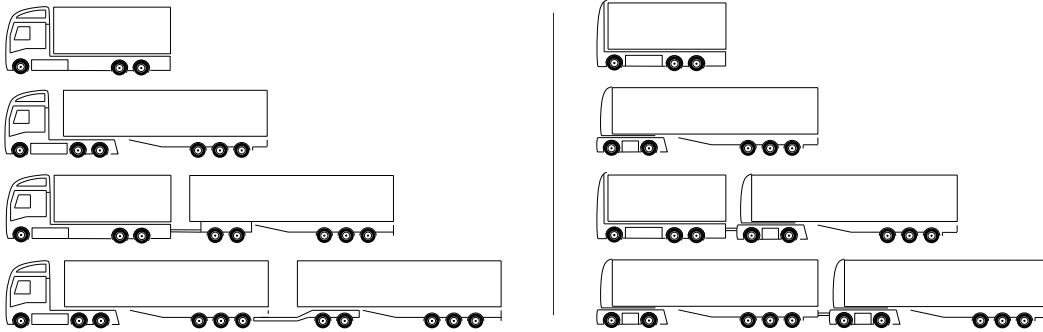
Using the above postulates, the problem could be divided into series of sub-problems similar to the case study presented in paper (I). Solution of all sub-problems yielded optimum vehicle-infrastructure candidates forming a look up space that could be used for optimizing fleet composition and size.

The basic achievement of paper (III) is the methodology presented for solving the defined problem as well as showing the interconnection between vehicle-transportation design parameters. In traditional FSMVRP there exists enormous number of feasible routes and a limited number of vehicle types. While, one of the main steps in the proposed methodology was to convert the huge problem to a problem with enormous number of vehicle types and limited number of feasible routes. This step was motivated by one of the conclusions of paper (I) stating that, in presence of PBS, vehicle hardware is less sensitive to the selection of routes, thus vehicle propulsion design and VRP could be decoupled in some cases. A colse-to-optimum fleet could be obtained by solving four different sets of optimization problems, three of which were solved using particle swarm optimization (PSO) [42].

The main outcomes of paper (III), among all others, are according to followings.

- Freight vehicle propulsion design is influenced by the route, transportation mission, and recharging power (in case of electric vehicle), as well as transportation boundaries, such as loading/unloading schemes.
- Fleet of long heavy combination vehicles with the corresponding optimized propulsion system could result in about 50% lower TCO than that in a fleet of rigid trucks.
- Optimum fleet composition as well as vehicles optimum hardware are sensitive to daily operation time length and freight volume/mass flow.
- In long combination vehicles, additional semitrailers come up as solutions for loading/unloading in many missions giving a priority of having propelled axles to dolly.
- Through use of integrated vehicle-infrastructure and fleet design, profitability of battery electric heavy-vehicle combinations can be increased, thus they can compete against their conventional combustion-powered counterparts in wider ranges of transportation missions.
- Charging power, duration time of charging and loading/unloading along with other factors affect the optimum size of batteries.
- For the studied missions, battery electric heavy vehicles (BEHVs) result in lower TCO than that of hybrid and combustion-powered heavy vehicles (CPHVs), if the volume constraint is active corresponding to low-density transported freight, such that gross combination mass is not reached even when large batteries are employed.
- If many vehicles present in a mission then infrastructure can be shared affecting optimum size of batteries as well as competitiveness of battery electric heavy vehicles in a positive manner.
- Battery electric heavy vehicles benefit more compared to hybrid vehicles from improvement in battery quality.
- For the missions involving long stop times, CPHVs result in lower TCO compared to hybrid and electric vehicles, mainly due to a high depreciation of purchase cost of hybrid and electric vehicles and low utilization.

Furthermore, future reduction in battery price, increase in diesel price, tax incentives, and extension of vehicle service life all contribute to even more competitive electric heavy-vehicle combinations.



**Figure 3.3:** *Different vehicle sizes. (left) vehicles driven with a human driver on-board; (right) ADS-DVs. From smallest to largest they are referred as rigid truck (RT), tractor-semitrailer (TS), Nordic combination (NC) and A-double (AD). (Re-produced from paper (IV)).*

As it was mentioned before, the main focus of this thesis was offering best vehicle-infrastructure solutions in on-road freight transportation, trying to include most important aspects influencing it in near future. According to predictions [1], driving automation constitute about 10% of total revenue in truck market by 2025. Deployment of freight vehicles equipped with high and full driving automation systems (DAS) will have a substantial impact on freight transportation and logistics [8]. According to SAE standard [34], high and full DAS respectively refer to levels 4 and 5, where, the presence of a human driver is not needed on-board in the vehicle. Also, according to the same standard, vehicles equipped with high/full DAS are called Automated Driving Systems-Dedicated Vehicles (ADS-DVs). In **paper (IV)**, it was discussed that ADS would also influence other vehicle systems such as propulsion, specially in battery electric heavy vehicles (BEHVs). Moreover, the impact of ADS has been studied on optimum propulsion systems and infrastructure both in BEHVs and CPHVs; while considering transportation missions with different characteristics, i.e. different driving ranges (distances between loading/unloading or charging stations), hillinesses, average reference speeds and vehicle sizes. The study, however, did not include hybrid vehicles. Different vehicle sizes with/without a human driver on-board have been depicted in Fig. 3.3.

Vehicle-infrastructure design variables included size of ICE, type and number of electric motors, type and size of battery packs, charging power and loading/unloading scheme. In order to make vehicle utilization indepen-

dent of filled capacity, missions have been defined such that vehicles travel always fully loaded up to their gross mass. The most important findings presented in paper (IV) are according to the followings.

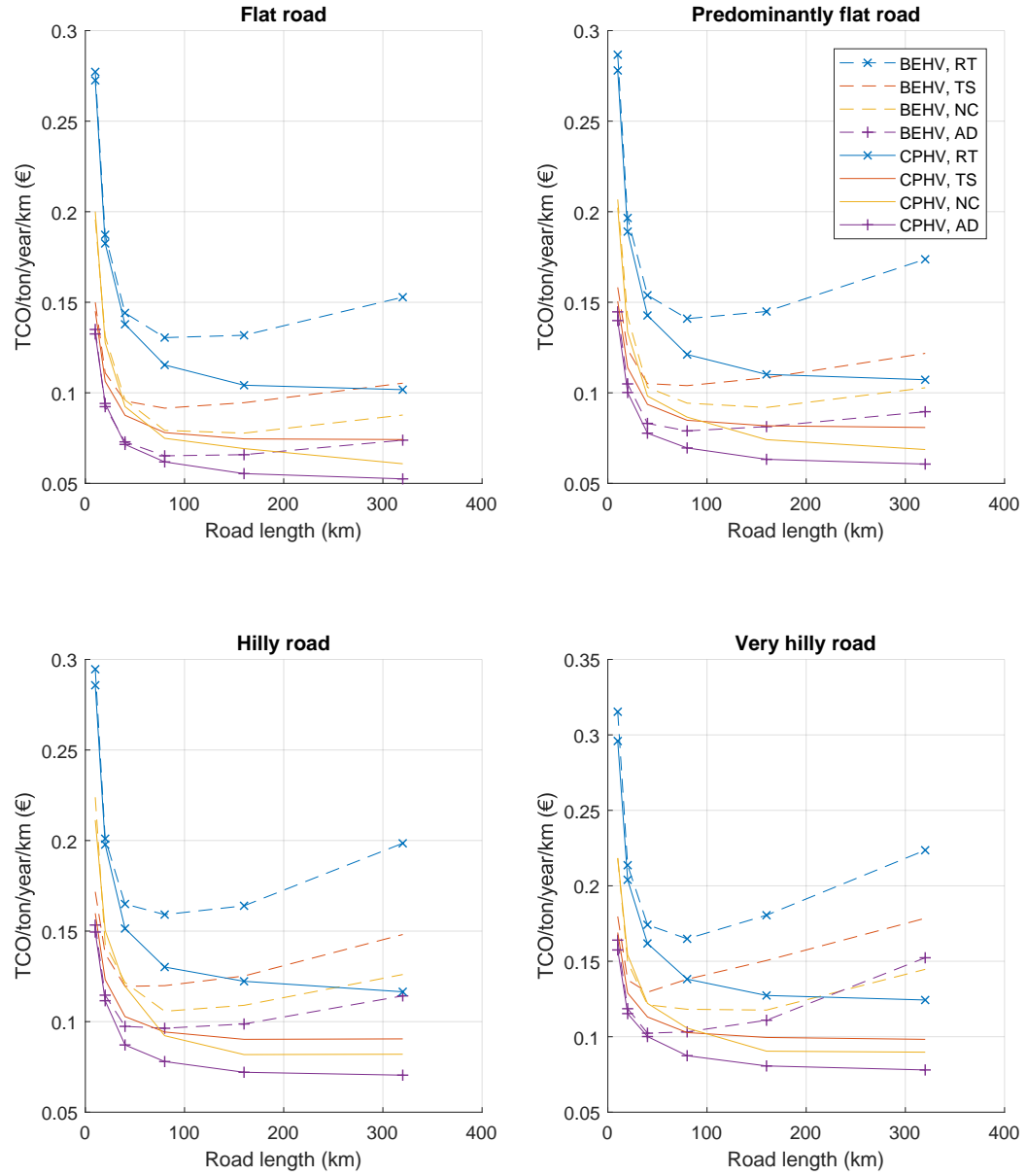
- The optimum propulsion setup differs between BEHVs equipped with ADS and these vehicles with a human driver, while no difference in ICE size was observed in CPHVs.
- ADS make BEHVs more competitive to combustion-powered counterparts, such that they remain profitable for increased travel ranges by a factor of four compared to profitable travel range of BEHVs driven by a human driver.
- The reduction of TCO caused by ADS was observed to be between 27% and 46% for BEHVs and between 11% and 41% for CPHVs on transportation missions with different characteristics.
- The reduction of TCO caused by ADS with very low cost of transport mission management system was observed to be between 40% and 78% for BEHVs and between 20% and 70% for CPHVs on transportation missions with different characteristics. Corresponding trends have been provided in the paper.
- BEHVs equipped with ADS tend to have lower optimal speeds than that of vehicles with a human driver.
- It would be less expensive for BEHVs equipped with ADS (up to 10% of TCO) than CPHVs equipped with ADS (up to 25% of TCO) to drive in low speeds; for example, at a speed of 50 kph because of safety reasons. Thus, If vehicles equipped with ADS have such speed limitations, they are more motivated for BEHVs than for CPHVs on many transportation missions.
- If a similar propulsion hardware as in a BEHV with a human driver is used in a BEHV equipped with ADS then TOC might increase between zero and 25% depending on transportation mission and vehicle size.
- Larger vehicles have lower profit margin of employing ADS, mainly because of lower share of driver cost compared to total cost.
- Increased hilliness of the road has a negative effect on competitiveness of BEHVs, mainly because of high power requests uphill that requires large batteries.
- Large vehicle sizes yield lower TCO in all missions including short travel distances down to 10 km, in case of quick loading/unloading and full capacity utilization.

## 3.2 Discussion

In the first paper, it was concluded that long vehicle combinations are not cost-optimum on short routes. This conclusion, however, could seem contradictory to conclusions drawn in paper (IV). In the forth paper it could be observed that a long vehicle combination yields a TCO about 50% of that of a rigid truck on short routes down to 10 km. Long vehicle combinations show better performance on long routes, however, they might be also good on short routes, refer Fig. 3.4, provided that the utilization rate is high. High utilization resulted by short loading/unloading time as well as employing the vehicles 24 hours per day through the entire vehicle service life. An optimum loading/unloading was found through a vehicle–infrastructure optimization in the forth paper, where goods were loaded/unloaded quickly with the lowest cost using a straddle carrier, thereby resulting in an increase in utilization rate of the long vehicle combinations despite frequent stops. However, this was not the case in the first paper where loading/unloading took place by on-board waiting and only 10 h working per day. On-board waiting corresponds to the case where pallets of goods are loaded/unloaded one by one. Figure 3.4 depicts annual TCO per unit freight transported and per kilometer-traveled for various optimized vehicle-infrastructures on different missions. It can be observed that long combination vehicles perform well on short routes for most of scenarios. An exception is seen for Nordic combination where a single straddle carrier is used to lift both containers, one after another, resulting in a longer loading/unloading time and consequently lower utilization. In case of A-double similar loading/unloading scheme is applied, however, loading capacity of the first container is higher than that of Nordic-combination resulting in a lower annual TCO per unit freight transported and per kilometer-traveled. Figure 3.5 depicts the same curves but for ADS-DVs. Most of the conclusions drawn in paper (IV) could be realized by analyzing these two figures.

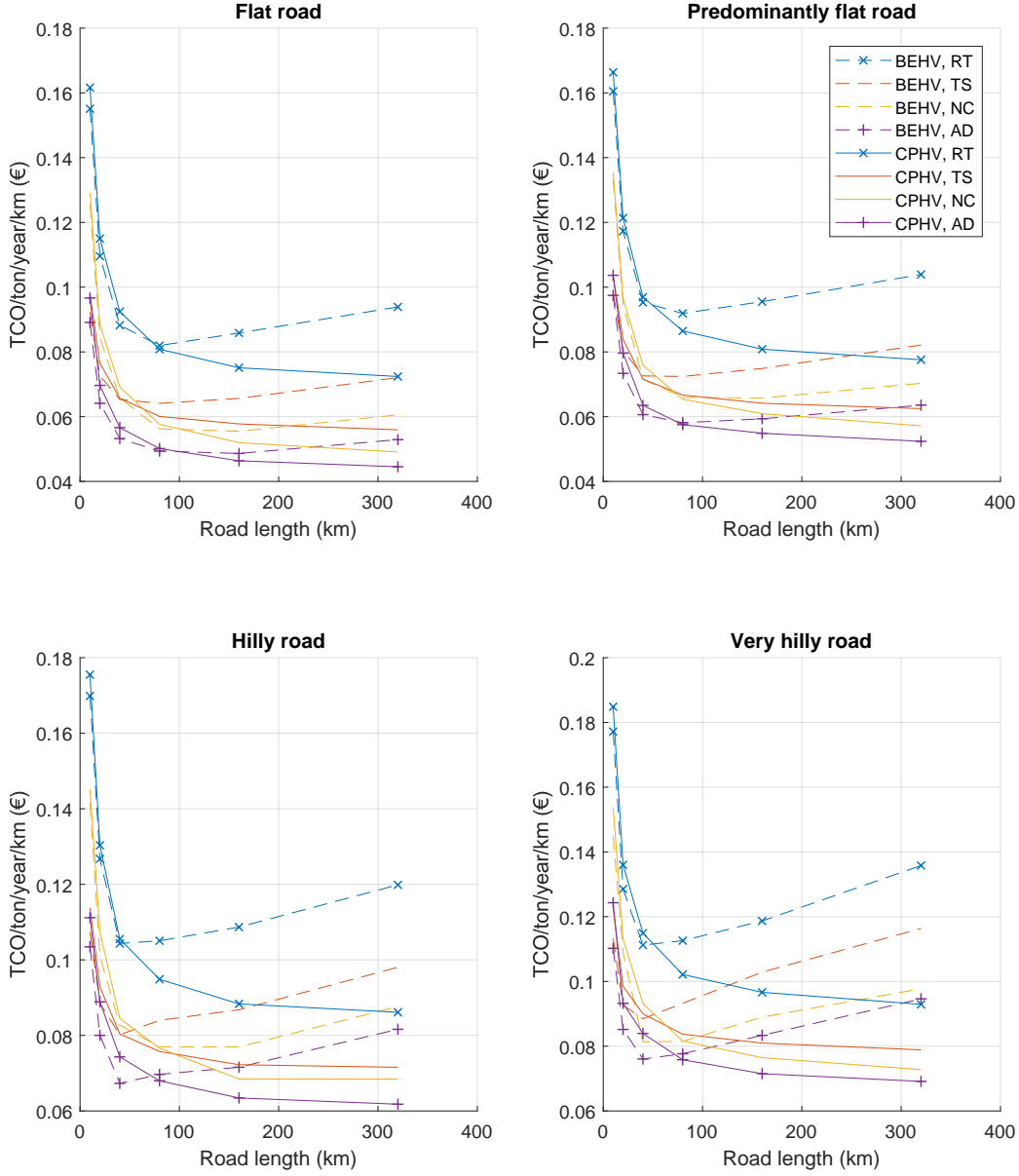
In this thesis it was observed that there exist many interconnected contributing factors to the successfulness of a transportation solution such as payload, weight and volume of goods, operating range, average speed, available routes, working time, operational environment, energy consumption, vehicle size, vehicle hardware, fleet composition, number of vehicles, utilization rate, infrastructure and logistics. In addition, charging infrastructure and battery characteristics are essential for transportations involving electric vehicles. They have been all studied in this thesis and it has been demonstrated

## Vehicles driven by human driver



**Figure 3.4:** Annual TCO per unit freight transported and per kilometer-traveled of vehicles driven by human driver for various optimized vehicle-infrastructures on different missions.

## ADS-DVs



**Figure 3.5:** Annual TCO per unit freight transported and per kilometer-traveled of ADS-DVs for various optimized vehicle-infrastructures on different missions.

that they all jointly influence the cost function. Looking at the components of the cost function (3.1), i.e. annual TCO per unit freight transported  $C_t$ , three main components may be realized: operational cost  $c_{opr}$ , depreciation cost  $c_{dep}$  and amount of freight transported  $f_{tr}$ .

$$C_t = \frac{c_{opr} + c_{dep}}{f_{tr}} \quad (3.1)$$

The mentioned factors all contribute to each of these components. Minimum TCO can be a measure of a good transportation solution. However, another measure that may partly explain quality of a transportation solution is utilization rate or efficiency of transportation. Among different definitions in literature, overall physical efficiency  $E$  is defined according to [35] as follows.

$$E = T \cdot D \cdot S \cdot C \quad (3.2)$$

where,  $T$  denotes the percentage of the available time that the vehicle is actually utilized,  $D$  represents the percentage by which the profit is reduced by not using the shortest route,  $S$  is the percentage by which maximum profit is reduced by not traveling at optimum speed, and  $C$  denotes the percentage by which maximum profit is reduced by not traveling at optimum capacity. Each of these factors may be divided into partial efficiencies. It has been observed, in this thesis, that each of these factors depend on the vehicle propulsion. Moreover, rather than maximizing utilization, an optimum utilization must be determined for each vehicle-transportation mission separately. The optimum utilization might be different from the maximum value. In that case, utilization should not be used as a fixed measure for evaluating the quality of transportation. For example,  $E$  should be always maximized for CPHVs considering the maximum road speed limit. On the other hand, in case of BEHVs, the optimum speed is different from the maximum road limit; in addition, an optimum  $T$  might not be the maximum available value, since, for example, applying reasonable charging power favors maximum power of fast charging considering battery degradation cost. So an efficiency of transportation defined in Eq. (3.2) or utilization level should be used as a quality measure of transportation for a given vehicle and within a given mission, not a measure between vehicles and missions with different characteristics.

Finally, it must be noted that solutions proposed in this thesis are sensitive to the missions defined, vehicle models and input data provided. How-



ever, drawn conclusions and the methodology of determining the optimum fleet are generally applicable.

### 3.3 Conclusion

Optimization-based design helps agile market adaption, profitable businesses specially in case of electrification and automation, as well as green transport; provided that sufficiently accurate models and input data are available. Engineering decisions through long discussions might not be accurate and agile, but necessary for modeling and parameterization. Through implementation of optimization processes, this thesis had a contribution to enhance road freight transportation efficiency and profitability. Such a optimization-based design made it possible to realize interconnection between optimum vehicle hardware in terms of propulsion and factors defining transportation mission and operational environment. In case of electric vehicles, vehicle propulsion system should be designed knowing the use-case and transportation environment where the fleet vehicles are intended to be employed. Implementing integrated vehicle-transportation design yields competitive solutions reducing total ownership cost up to 50% in case of fleet and up to 35% in case of a single battery electric vehicle. However, a proper description of the use-case and system boundaries must be available through clear communication between stakeholders.

### 3.4 Future work

As it was mentioned, there were some limitations in implementing optimization based vehicle-transportation design. The tactical and operational levels of decision making could not be taken into account properly. Tactical and operational decisions refer to actions taken during dynamic driving task with the time span in minutes and seconds, respectively. These actions contribute to energy consumption, as was discussed in paper (II), as well as vehicle maneuvering. In case of having many propelled axles distributed on several vehicle units as a solution of propulsion system optimization, total power should be distributed between them in a fashion to guarantee both energy efficiency and stability. A poor power distribution strategy might cause lateral instability of vehicle during maneuvering, for example, in a case when

the dolly provides all requested power pushing the front units on a road with a low friction [5]. Therefore, future work includes the followings.

- Building models and control strategies to properly describe driving in tactical and operational action levels for the defined problem, such as models of vehicle lateral dynamics.
- Optimal distribution of propulsion and braking between axles.
- Studying the effect of lateral stability constraints.
- Longitudinal speed optimization of BEHVs regarding lateral stability, for a fixed given position/time horizon.
- Assuming that charging stations belong to third parties with variable prices of electricity, to study how the charging should be performed/distributed among the visited charging stations.
- Real vehicle testing for verifying models and transport measures, especially for vehicles with many propelled axles, distributed on several vehicle units.

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